DR18

REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
12-2-96

3. REPORT TYPE AND DATES COVERED
Final Technical Report

4. TITLE AND SUBTITLE OF REPORT
Scanning microcathodoluminescence and near-field optical scanning microscopy of nanostructures in semiconductors

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER:
N00014-93-1-0910-F

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER:
Office of Naval Research

11. SUPPLEMENTARY NOTES:

19961226 101

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE
Unclassified

13. ABSTRACT (Maximum 200 words)

14. SUBJECT TERMS

15. NUMBER OF PAGES:
Five

16. PRICE CODE
N.A.

17. SECURITY CLASSIFICATION OF REPORT:	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

Scanning Microcathodoluminescence and Near-Field Optical Scanning Microscopy of Nanostructures in Semiconductors (AASERT Award)

Office of Naval Research
Grant No. N00014-93-1-0910
Final Report
December 2, 1996

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Introduction

This report briefly summarizes work completed on the above grant during the time period of June 1, 1993 to May 31, 1996. The grant, an AASERT Award to support the work of one graduate student, supplemented a larger ONR grant (N00014-90-J-1306) and expanded the effort in that grant to scanning tunneling luminescence(STL) microcathodoluminescence (μ-CL), and near-field scanning optical microscopy (NSOM). The objective has been to use these new techniques for investigating local optical properties of surfaces and small structures and relating these to morphological properties and structural defects. The project has been quite successful, in that we were able to develop a functional STL capability and use it for initial studies of localized luminescence on GaAs and GaN. In addition, the objective motivated research on improved scanning technology for scanned-probe instruments, which has led to an invention disclosure and the filing of a patent application by the University.

Scanning Tunneling Luminescence

A significant accomplishment of this grant was the establishment of a scanning tunneling luminescence/microcathodoluminescence capability and using it to perform initial investigations on GaAs vertical-cavity surface emitting lasers (VCSELs) and on the wide-band-gap semiconductor GaN. STL shows great promise as a local probe of electronic structure and optical properties. The implementation of the technique is relatively straightforward when utilizing a working STM. In standard cathodoluminescence, a high-energy electron beam incident on a surface excites photons whose energy and intensity reflect electronic processes in the material. In STL/μCL, the STM tip is used as the tunable low-energy source of electrons. With a sensitive spectrometer and detector luminescence from very small regions of the sample can be detected. The system is directly compatible with existing STM chambers. We implemented STL through the addition of a lens on the STM that has a high collection efficiency. The light come out of the vacuum system into the detector. We are able to obtain simultaneous 2-dimensional topographic and luminescent images by scanning the tip and measuring the emitted light gated to the position of the point of carrier injection underneath the tip. The tunneling current provides the topographic image while the light provides the luminescent image.

The information obtained with STL is expected to extend our understanding of how dimensional constraints affect optical and electronic performance of compound semiconductors. For example, one should be able to probe the optical signals associated with steps, with different roughness of steps, with growth defects, and with rough surface morphology. Beyond this, one can probe shallow buried layers in multilayer films through injection of electrons. STL can also be used on cleaved multilayer films to probe the changes in electrical/optical properties as the composition changes from one layer to the next through a possibly intermixed or reacted zone at the interface.

The spatial resolution of the luminescence signal, one of the most important and interesting questions in the application of STL, depends on the sample temperature and the details of the current transport and distribution of the injected carriers. The focus of our initial work has been on mapping the spatial distribution of the signal on a nanoscopic scale. The very localized injected carriers will in any case allow for the majority of the luminescence signal to originate from a region much smaller than the conventional photo- and cathodoluminescence techniques. In our GaN studies, we found, surprisingly, that the spatial resolution was much better than expected: the existence of traps in the surface or near-surface region causes nonradiative recombination. In addition the mean free path of the injected carriers (holes for n-doped GaN) limits the spatial extent of the radiative recombination. A spatial resolution of the order of 1-2 nm was estimated.

Used in the cathodoluminescence mode (field emission from the tunneling tip when it is retracted), the instrument produces very bright luminescence from GaN. In this case electrons are injected. Apparently some of these higher-energy electrons reach the bulk to create electron-hole pairs that can then recombine to give off light. We have developed a model to explain the luminescence, as well as a noise-analysis procedure to demonstrate that the observed light is not simply noise. No obvious correlation with structural features such as steps was evident, suggesting that steps themselves do not act as recombination centers. More detailed analysis will be required to determine which defects correlate with the luminescence.

The STM/STL work on GaN has so far resulted in two publications in Appl. Phys. Letters, one published and one in press. A Ph.D. dissertation was completed on this work in August 1996 by Brad Garni, the student primarily supported on this grant. A long paper is in preparation. The APL is a photoelectron spectroscopy study of GaN surface cleaning procedures that points out that most work so far has been on contaminated surfaces. We performed this work to assess the quality of our own surfaces, which are of films grown in house by halide vapor phase epitaxy (HVPE) and by MOCVD. Films were grown by Tom Kuech.

Faster Scanning in Scanned-Probe Microscopes

An aspect of continuing effort and interest in SPM is the speed with which one can obtain an image. A related application of great technological interest is the use of SPM methods for possible future nanolithographies. The scanning speed limitation is a serious concern. As part of our instrument development efforts, we have been working, partially with support from this grant, on improved scanning speed in SPMs. This effort, by Steve Walker and based on a novel concept, was quite successful and led to the filing of an invention report and a patent application by the University. It is hoped that the technology developed here can eventually be transferred to the private sector for commercialization in a variety of applications in which rapidly responding piezoelectric materials are of use.

Publications

In addition to the patent application and the Ph.D. dissertation, two publications are a direct result of this support. One is in press at APL and the other has been published by PRL. A longer paper on STL on GaN surfaces is in preparation.